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CONSTRUCTION OF COLD MASS ASSEMBLY FOR FULL-LENGTH DIPOLES FOR THE SSC ACCELERATOR*

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Abstract

Four of the initial six 17m long demonstration dipole magnets for the proposed Superconducting Super Collider have been constructed, and the first one is now being tested. This paper describes the magnet design and construction of the cold mass assembly. The magnets are cold iron (and cold bore) 1-in-1 dipoles, wound with partially keystoned current density-graded high homogeneity NbTi cable in a two-layer cos θ coil of 40 mm inner diameter. The magnetic length is 16.6 m. The coil is prestressed by 15 mm wide stainless steel collars, and mounted in a circular, split iron yoke of 267 mm outer diameter, supported by a cylindrical yoke (and helium) containment vessel of stainless steel. The magnet bore tube assembly incorporates superconducting sextupole trim coils produced by an industrial, automatic process akin to printed circuit fabrication.

Introduction

This paper reports on the design features and cold mass construction details of the first six full length (17 m) demonstration dipoles for the Superconducting Super Collider (SSC) R&D program. Construction of the complete magnets (including cryostats, and their testing) is a collaborative effort between Brookhaven National Laboratory, Lawrence Berkeley Laboratory, and Fermilab. In this collaboration, the cold mass is assembled at Brookhaven. The magnet, also known as Reference Design D, consolidates the principal features of earlier Reference Design A and B[1], and draws on the collective experience with magnets for the CBA Project[2] and the Tevatron.[3] The SSC Conceptual Design is based on high field (≥ 6.0T) superconducting dipole magnets, allowing a relatively "modest" ring circumference (90 km for a guide field of 6.6T). The high field is achieved with newly developed high homogeneity NbTi conductor. Additional magnet features include a relatively small (40 mm) bore and long (16.6 m) magnetic length. The present magnets incorporate distributed, superconducting sextupole trim coils produced by an automated, precision technique. (The design does not utilize the 2-in-1 yoke concept of Reference Design A successfully demonstrated in earlier model magnets:[4] a 1-in-1 design was ultimately favored primarily for machine-operational reasons.) A detailed description of the magnet design can be found in the SSC Conceptual Design Report and Attachment B of that report, issued in the spring of 1986.[5]

Magnet Design

Figure 1 shows a cross section of the collared coil, and Fig. 2 a section of the overall cold mass assembly with collared coil, iron yoke, and yoke support tube. The inner diameter of the two-layer coil is 40 mm, and the outer diameter of the iron yoke is 266.7 mm. Omitted from Fig. 2 is the external cryostat, including thermal shields, superinsulation, cryogenic headers, vacuum vessel and magnet support system, not covered in the present paper. Figure 3 shows a cross section of the bore tube assembly, including beam tube and superconducting correction coil winding. The overall (coil) length of the magnet is ≈ 17 m. A few design parameters are listed in Table 1.

Table 1. Main Dipole Parameters

Magnetic length [m]	16.6
Overall (coil) length [m]	16.75
Yoke length [m]	16.86
Bore tube I.D. [mm]	32.64
Inner coil, I.D. [mm]	40.00
Outer coil, O.D. [mm]	79.86
Yoke I.D. [mm]	111.4
Yoke O.D. [mm]	266.7
Yoke containment vessel, O.D. [mm]	276.2
Cold Mass [kg]	6759
Operating field [T]	6.6
Current [kA]	6.5
Stored energy [MJ]	1.12

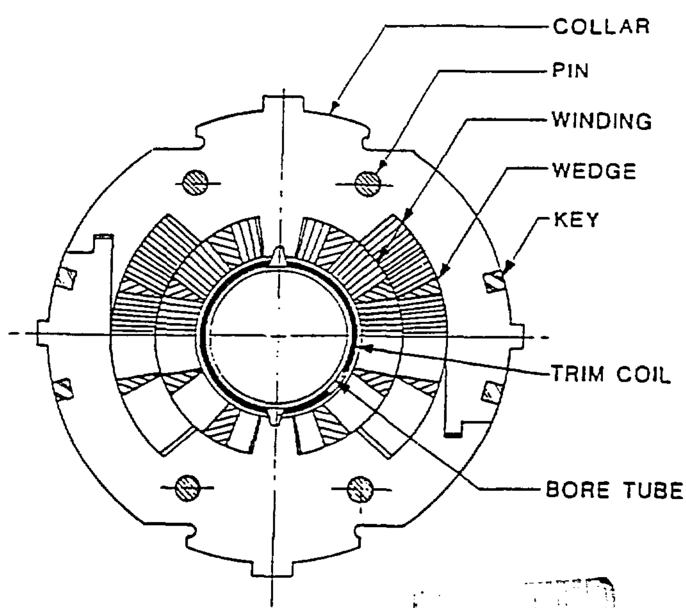

Figure 1. Cross section of collared coil assembly showing bore tube, main coils and stainless steel collar. The trim coil mounted on the outer diameter of the bore tube is not explicitly shown.

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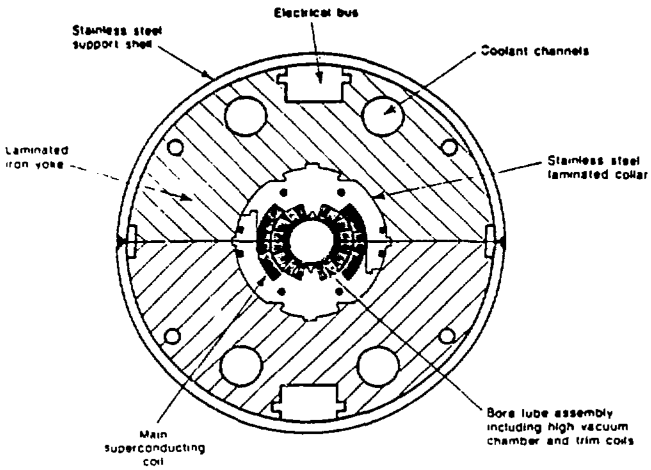

Figure 2. Overall cross section of magnet, showing collared coils mounted in split iron yoke and yoke support (and helium containment) vessel.

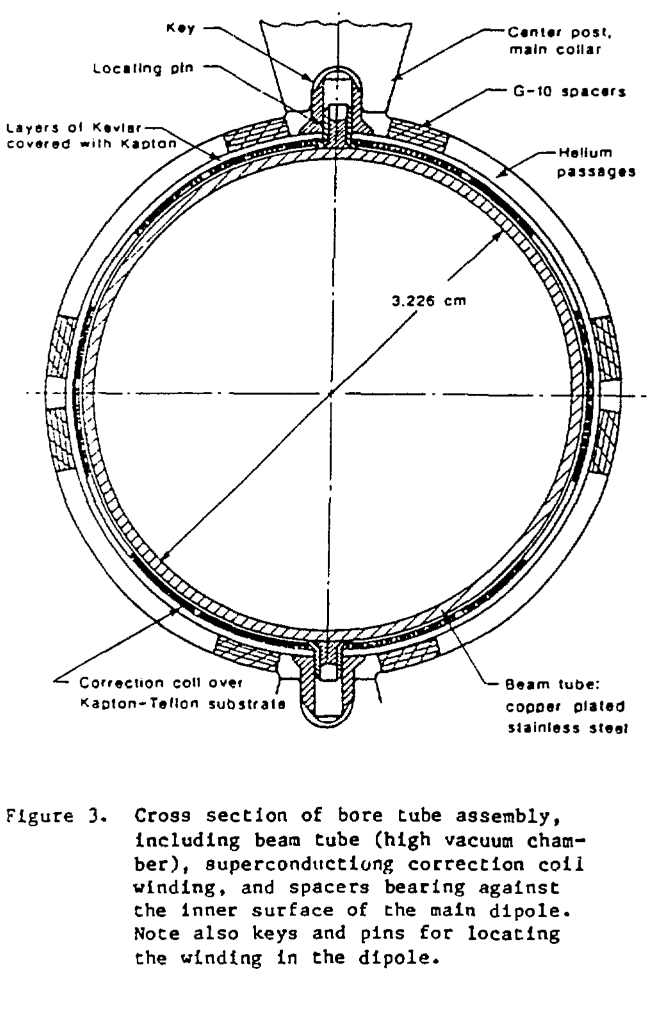

Figure 3. Cross section of bore tube assembly, including beam tube (high vacuum chamber), superconductiong correction coil winding, and spacers bearing against the inner surface of the main dipole. Note also keys and pins for locating the winding in the dipole.

The calculated transfer function for a central field (B_0) of 6.6T is 1.014 T/kA, corresponding to a current of 6.51 kA. The drop in B_0/I at 6.6T relative to its low field value, because of iron saturation, is about 2%. The measured and calculated transfer functions agree rather well, typically within 0.2%.

On the outside of the stainless steel cold bore tube is mounted a distributed (17 m long) sextupole correction winding, required for compensating systematic errors and magnetization effects in collider operation. The multipole pattern is produced by embedding the superconducting wire in a Kapton sheet by an automatic technique developed by the Multiwire Corporation for printed circuit applications. Between the trim coil and the main dipole coil are longitudinal insulator strips (Fig. 3) spaced to furnish annular helium passages in forced-cooling operation, and to locate the trim coil concentrically within the main dipole coil.

Both inner and outer dipole coil layers are wound from a partially keystoned, flat cable of the Rutherford/Tevatron type, produced from high homogeneity NbTi wire. The nominal (bare) conductor dimensions are as follows. Inner: strand diameter 0.808 mm; cable radial width 9.30 mm, mean thickness 1.46 mm, keystone 1.7°. Outer: strand diameter 0.648 mm; cable radial width 9.73 mm, mean thickness 1.17 mm, keystone 1.2°, The keystone angles are the maximum possible values without incurring severe wire distortion. The lack of full keystoning commensurate with the coil aperture and cable size is compensated by insulated wedges in the coil cross section. The wedges also furnish additional degrees of freedom in the field-shaping optimization procedure. The field in the outer coil is lower than in the inner coil: B_{max} (outer) = 0.364 B_0 vs. B_{max} (inner) = 1.046 B_0. Therefore, to ensure cost-effective superconductor utilization, the inner coil layer (16 turns/quadrant) is wound from a 23-strand cable of Cu:SC ratio 1.3:1 and the outer layer (20 turns) from a 30-strand cable (1.8:1). The current density of either cable is ~ 2100 A/mm^2 (5T, 4.2K). The conductor filament size in the first two magnets is 20 μm, and 5 μm in the subsequent magnets. The latter is the diameter specified in the SSC CDR, chosen to minimize the demands on the distributed sextupole correction winding.

Both coil layers are powered in series. Cable insulation consists of an overlapping layer of Kapton film (0.0508 mm thick) followed by a layer of epoxy-impregnated fiberglass tape (of nominal 0.0508 mm thickness when the winding is under compression). The first two magnets retain a strictly provisional feature from Reference Design A: their coil ends are flared out to increase the minimum bending radius, allowing the possibility of substituting prereacted Nb_3Sn. Experience with model magnets has shown, however, that flared ends are not necessary for NbTi, and subsequent magnets utilize straight coil ends.

The coils are compressed with 15 mm wide collars of non-magnetic stainless steel, similar to those developed for the Tevatron except that no welding is involved; pins and keys are used instead. They provide the necessary restraint to maintain the coil under a compressive stress of about 6 kpsi. With the cold iron separated from the coils by the collar width, the iron contributes ~ 1.4T to the 6.6T central field, but saturation effects are quite small. (The change in the sextupole harmonic is 2 x 10^{-4} of the dipole, at 1 cm.) An important advantage of collars is that they allow testing a magnet at room temperature before insertion into the iron yoke.

The yoke laminations, punched from 1.5 mm thick sheets of low-carbon steel, contain keyways for accurately locating the collared coil assembly. The two large rectangular slots (Fig. 2) carry the main and diode bypass electrical bus (top) and correction element leads necessary for operation in a magnet string. The four large holes are channels designed to bypass most (110 g/sec) of the 4 atm. supercritical helium mass flow; only about 1 g/sec is needed for transferring heat in the coil region. The yoke and helium containment vessel is fabricated from 4.8 mm thick stainless steel half shells welded shut on the midplane. Fiducial marking plugs extend through the helium containment shell. These provide accurate alignment references for relating the position of the magnet to the external vacuum vessel. To ensure proper "lay" of the relatively wide cable and to minimize field enhancement in the four magnets incorpoating straight-ended coils, the end turns are spaced out axially by interleaving molded spacers and wedge extensions. In all six dipoles the iron yoke terminates before the coil end is reached; the remaining space is filled with matching laminations of stainless steel. (Future magnets will incorporate iron yokes extending over the coil ends, but with an inside diameter larger than in the magnet "straight section". This will still avoid field enhancement in the magnet ends, while also minimizing the external fringe field.)

Magnet Construction

The four coil sections of a dipole are wound separately on a laminated, convex mandrel in a microprocessor-controlled winding machine twice the length of a 17 m dipole (Fig. 4). The cable is fed from a quasi-stationary supply spool onto the mandrel which acts as a shuttle. A turn is initiated by winding the cable around one coil end with the mandrel rocking in unison to ensure a proper lay. Next, one side of a straight section is wound as the mandrel travels the requisite distance with the stationary reel paying out cable. The supply spool retraces it steps, laying cable around the other end of the racetrack-shaped path, and the turn is completed with the mandrel returning shuttle-fashion to its starting position. When all turns of a coil have been wound, molded end spacers are mounted. Finally, the coil-mandrel package is wrapped with tensioned Tedlar; in addition to securing the coil to the mandrel for the next operation, the Tedlar also performs the subsequent role of mold-release agent.

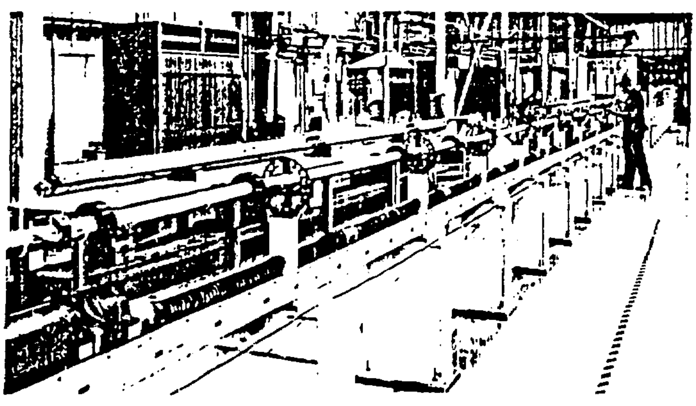

Figure 4. Coil winding fixture. The fixture is designed to accommodate dipole coil segments of arbitrary length up to a maximum length of 16.7 m.

The hydraulically operated, oil heated coil curing fixture (Fig. 5) is assembled from 1.5 m long module sections. The coil and mandrel are lowered as a unit into the concave fixture, previously prepared with additional mold-release and various tooling components in place. The coil is cycled through a heating sequence with side and end pressure applied in a particular order. The curing portion of the cycle takes place at 150°C for a period of approximately 100 minutes. The epoxy in the fiberglass conductor wrap is controlled so that none comes into contact with the wires during the cure.

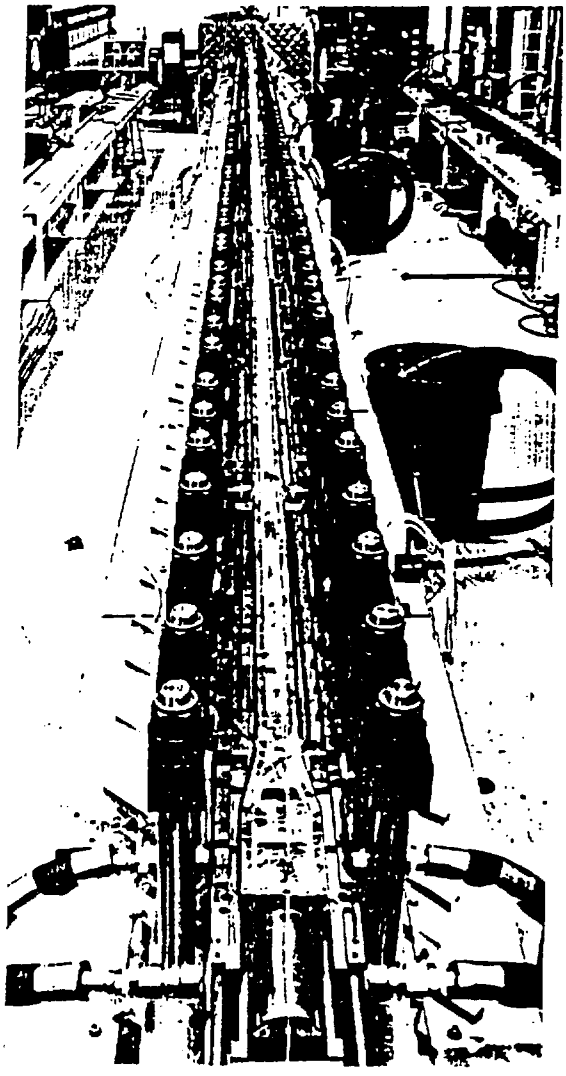

Figure 5. Oil-heated coil curing fixture, assembled from eleven 1.5 m module sections.

The coil sections are assembled around a stainless steel bore tube (34.5 mm O.D. by 1.0 mm thick) to which the trim coil has already been attached. During this assembly additional insulation is introduced: Kapton on the midplane (2 x 0.05 mm) and Kapton (0.05 mm) and a Teflon slip plane (0.05 mm) between coil layers. The collars, pre-assembled in packs, are assembled over the coil package already insulated on the O.D. with three layers of Kapton (0.127 mm each). They are compressed incrementally with a press and keys are inserted to keep them closed. (This operation is depicted in Fig 6). The material specified for the collars is Nitronic 40 stainless steel, a product of Armco, selected because it meets the strength requirements and also exhibits excellent magnetic (low permeability) properties at cryogenic temperatures. Keys, unlike welds, facilitate repair of magnets. Finally, the collared coils are mounted in the horizontally split iron yoke, previously assembled from module blocks. The key tabs on the midplane and vertical center line register the collared coil assembly in the yoke. The diameters of the collar and yoke are dimensioned so that the collars do not bear against the yoke and are therefore self-supporting. The last step is closing the yoke containment shell by a welding operation, with the top and bottom yoke subassemblies held in contact under pressure.

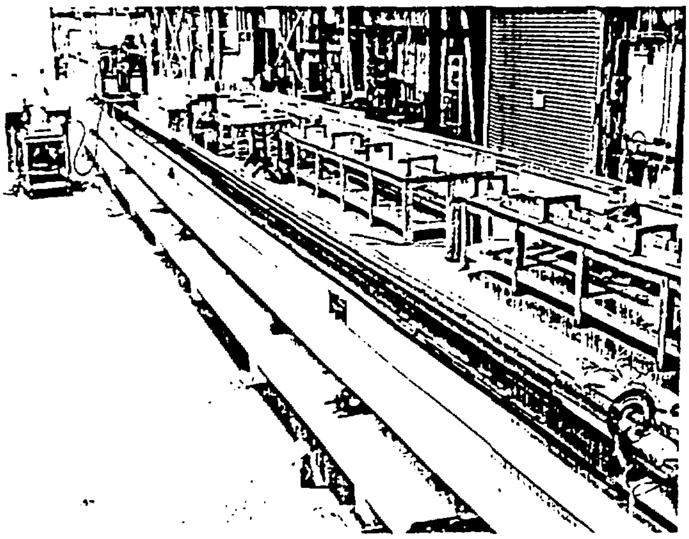

Figure 6. Collaring the first dipole. The incremental press can be seen at the far end. Note enlarged collar laminations in the coil ends (e.g. foreground) to accommodate flared coil ends in the first two dipoles.

Trim Coil Construction

The present group of magnets utilize sextuple trim coils manufactured by the Multiwire Corporation (future dipoles will incorporate octupole and decapole trim coils as well,. The industrial process employed allows wires to b˒ placed in a layer of fiberglass and epoxy with greater precision (± 25 μm) than can be achieved with conventional winding methods. The Cu-NbTi composite wires are bonded to a flat rectangular sheet of substrate and secured to the bore tube with a FEP-Teflon adhesive and an overwrap of FEP-impregnated Kevlar. Accurate positioning of the bore tube is achieved by aligning slots cut in the substrate onto guides attached to the bore tube. The bore tube is keyed to the dipole collars at the top and bottom. Spacers between the trim coil and the main coils limit flexure during operation (Fig. 3). Table 2 lists the principal mechanical parameters for the trim coil. The coil is designed for an operating current of ~ 5A at full field — approximately a factor of four below the critical current of the conductor.

Table 2. Trim Coil Parameters

Overall length [m]	16.8
Mean diameter [mm]	35.3
No. of turns	17
Wire dia., bare [mm]	0.20
Cu:SC ratio	1.65:1
Filament size (monofilament) [mm]	0.127

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